RIKEN Lunch Seminar July 26, 2012

The QCD Plasma Near Tc: An Update

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Outline

- Introduction: QCD plasma near Tc
- The geometry and physics of jet quenching
- Effect of light fermions on confinement transition
- Summary

X.Zhang, JL, PLB, arXiv:1202.1047 [nucl-th]
X. Zhang, JL, to appear soon
JL, arXiv:1109.0271 [nucl-th]
J.Jia, W.Horowitz, JL, Phys.Rev. C84 (2011) 034904
JL, Shuryak, Phys.Rev.Lett. 102 (2009) 202302
JL, Shuryak, arXiv:1206.3989

Some of You Might Recall…

Feb 2008 RIKEN Lunch Seminar on
“Magnetic quasi-particles in sQGP”

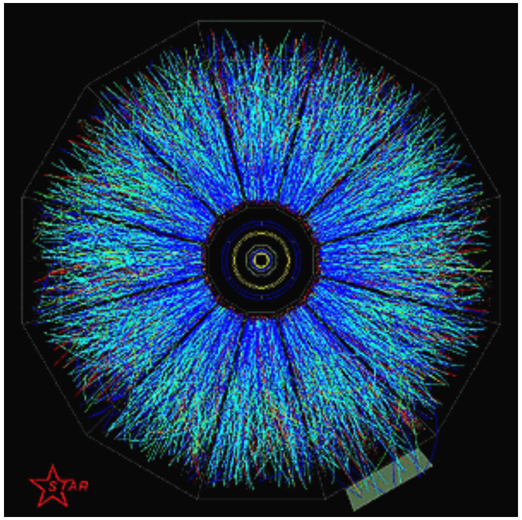
Nov 2010 RIKEN Lunch Seminar on
“The geometry of jet quenching”

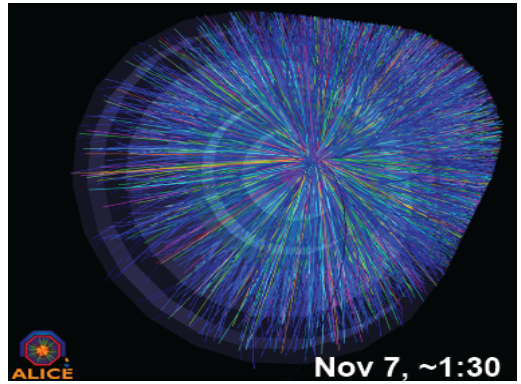
Today:
An update on new, exciting progresses.

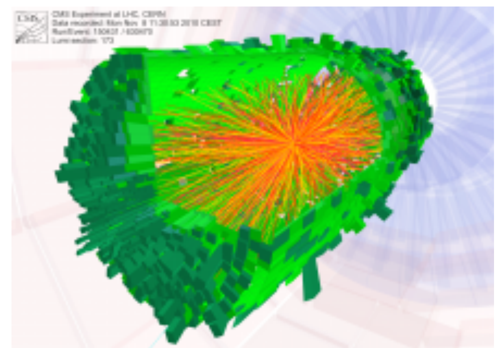
Hot QCD Matter from RHIC to LHC

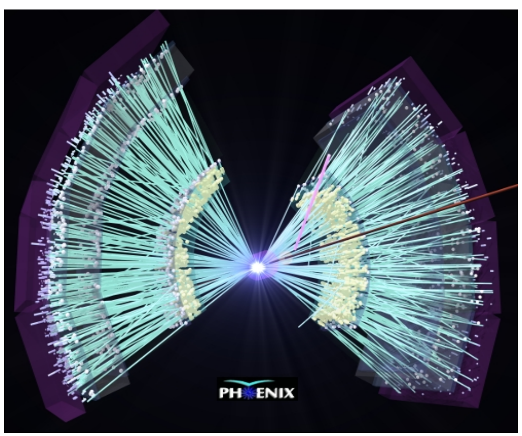
RHIC Event

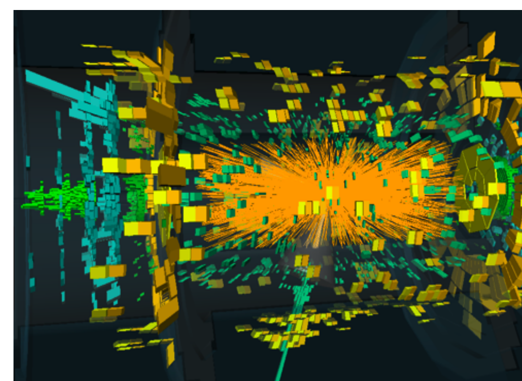
LHC Event











Beautiful “little bang” delivered !

Great lever arms !

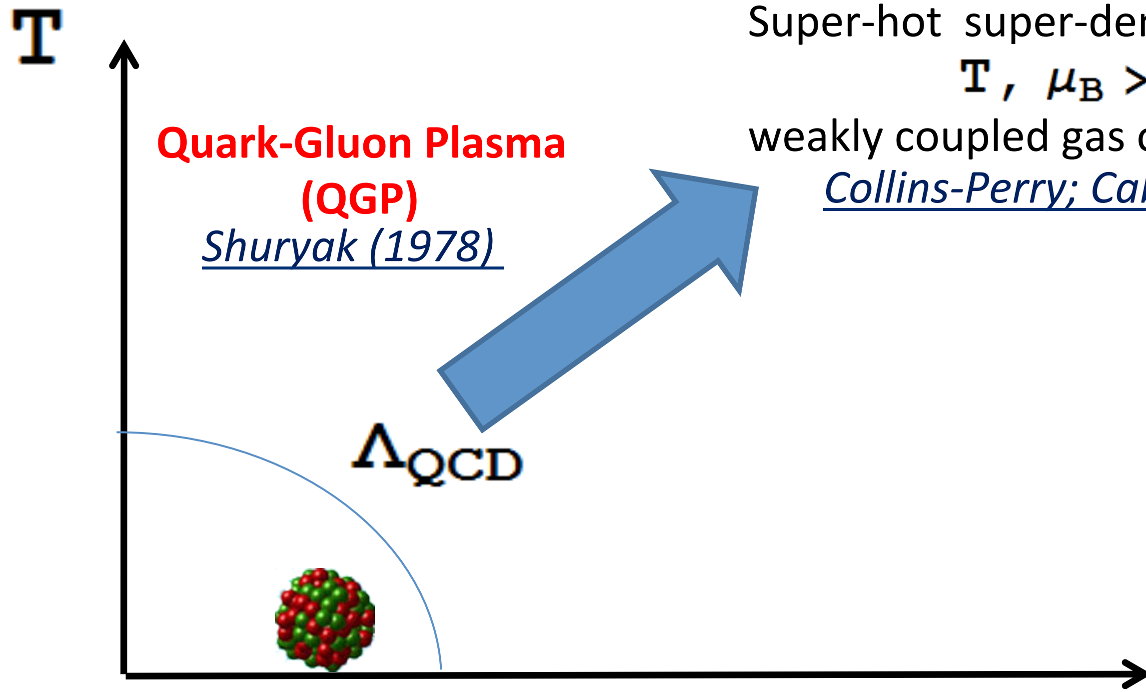
Asymptotically Free Matter?

Super-hot super-dense:

$$T,\ \mu_B >> \Lambda_{QCD}$$

weakly coupled gas of quarks and gluons

Collins-Perry; Cabibbo-Parisi (1975)



"Vacuum Engineering" (early 70's)

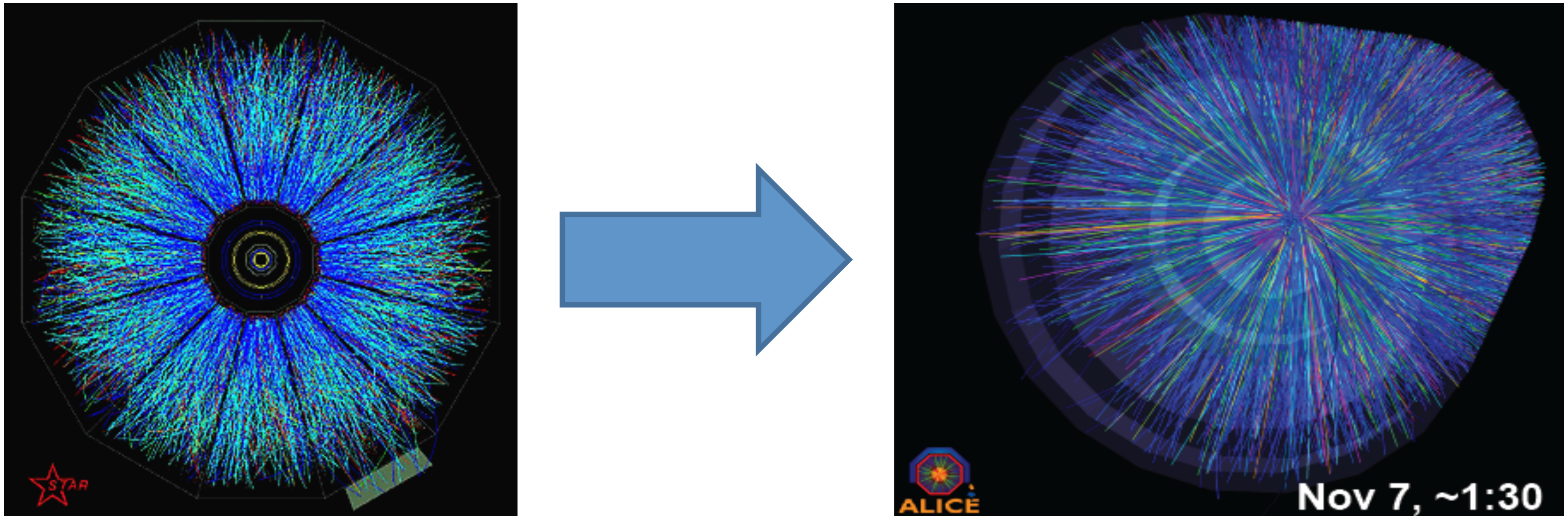
Highly nontrivial predictions from QCD ; μ

Deconfinement & Chiral Symmetry Restoration ?!

"To learn the small, we need the large."(T D Lee)

RHIC came with many surprises: a strongly coupled quark-gluon matter

Hot QCD Matter from RHIC to LHC



<u>Unique opportunity to better understand BOTH !</u>

•A more "perfect" fluid or less?

•A more opaque medium or less?

• How much closer are we getting to the "AFM"?

•Theoretically: what's the structure of the QCD matter at RHIC energy and how should that change at LHC energy?

• What to expect at the LHC top energy HIC?

Emergent QCD Matter Near Tc

T<< Lambda_QCD

T ~ Lambda_QCD

T>> Lambda_QCD

Vacuum: confined

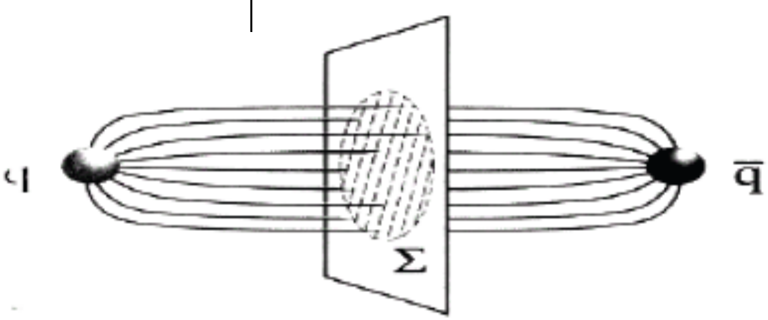
Tc

sQGP

wQGP: screening

T

RHIC



?

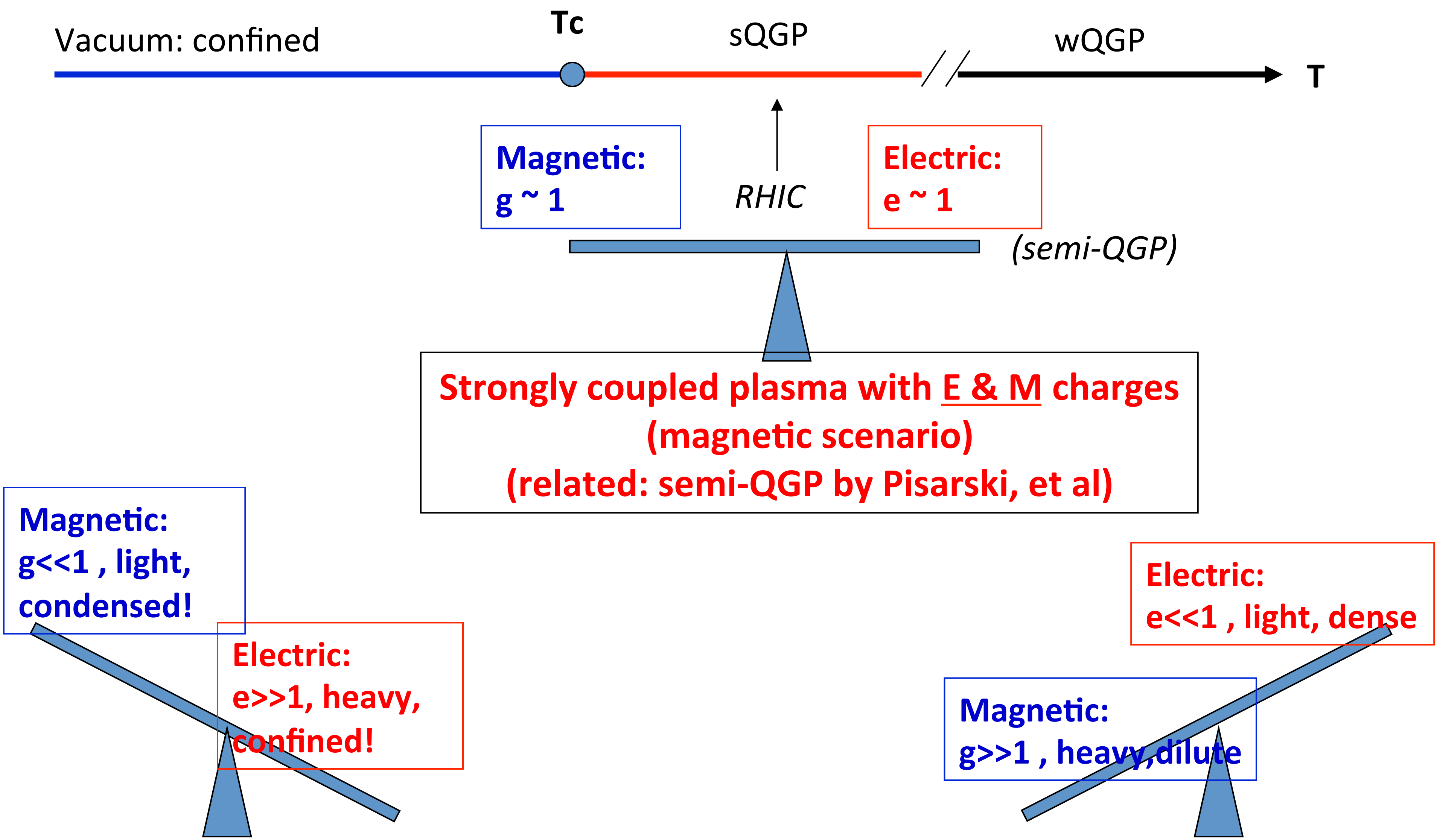
Electric Flux Tube:
Magnetic ***Condensate***

Dual superconductor
't Hooft ; Mandelstam late 70's
Manifested in Seiberg-Witten

Plasma of E-charges
E-screening: g T
M-screening: g^2 T

sQGP as an E-M See-Saw QGP

JL & Shuryak, PRC(07),PRL(08)



Magnetic Scenario for QCD Plasma Near Tc

- Generic E-M Duality: at strong gauge coupling, chromo-magnetic monopoles become the dominant degrees of freedom.

- Plasma close to Tc is special: a strong magnetic component, dominant around Tc.

- RHIC phenomenology is particularly sensitive to the properties of QCD plasma near Tc

- ***Rapid turn-off when getting away from Tc (------the quick message to take away)***

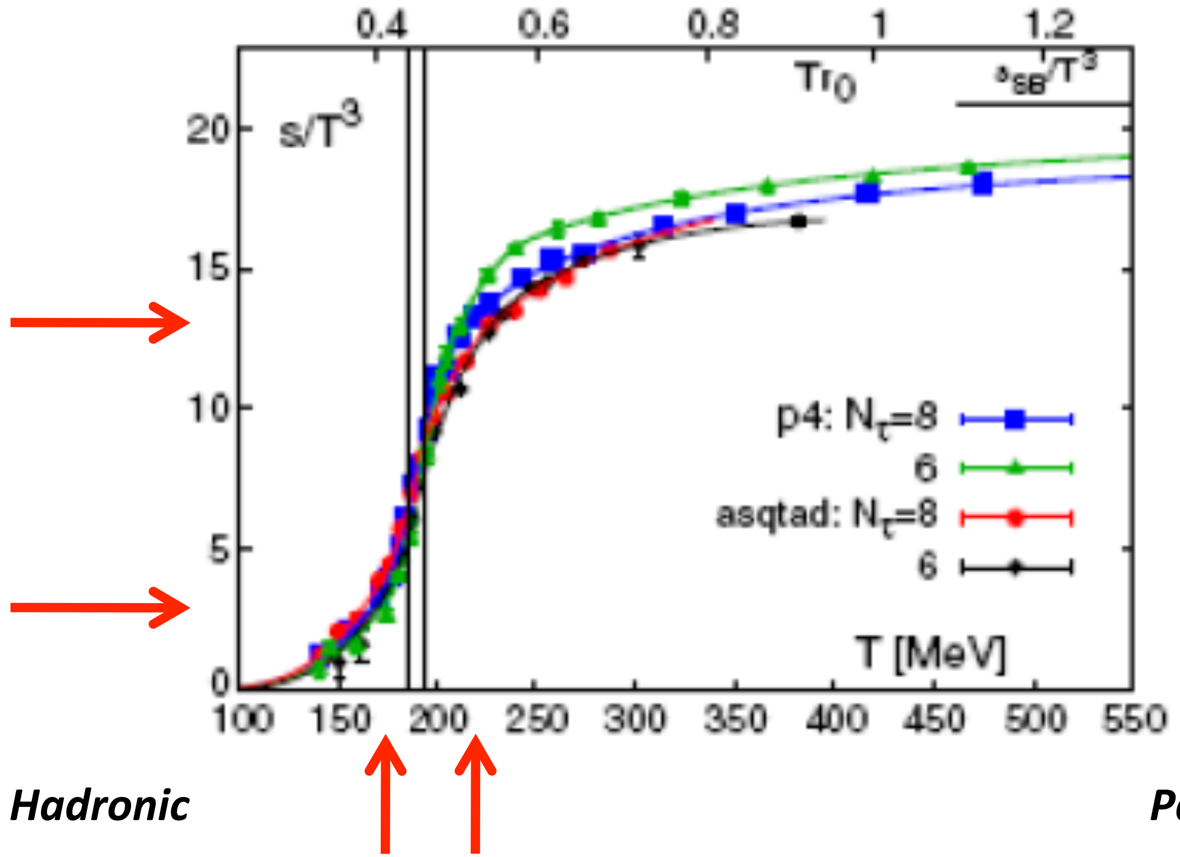
JL & Shuryak:
Phys.Rev.C75:054907,2007; Phys.Rev.Lett.101:162302,2008; Phys.Rev.C77:064905,2008; Phys.Rev.D82:094007,2010; Phys.Rev.Lett.102:202302,2009.

Near-Tc Matter: Thermodynamics

Near Tc: <u>a wide window</u> in terms of entropy density !

What is the nature of confinement transition?

Can H.I.C. help us understand the matter just about to confine?

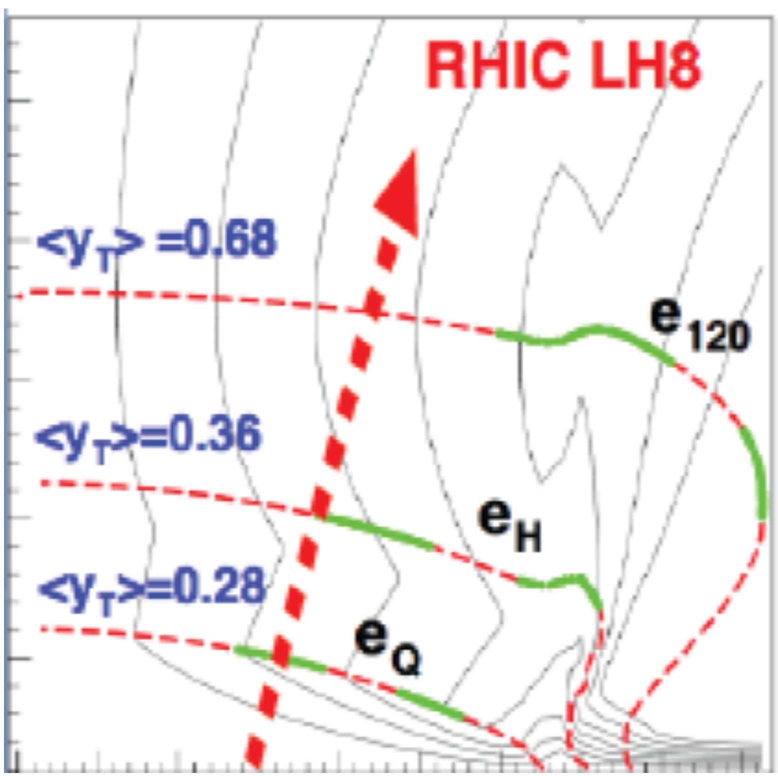


Hadronic ***Partonic***

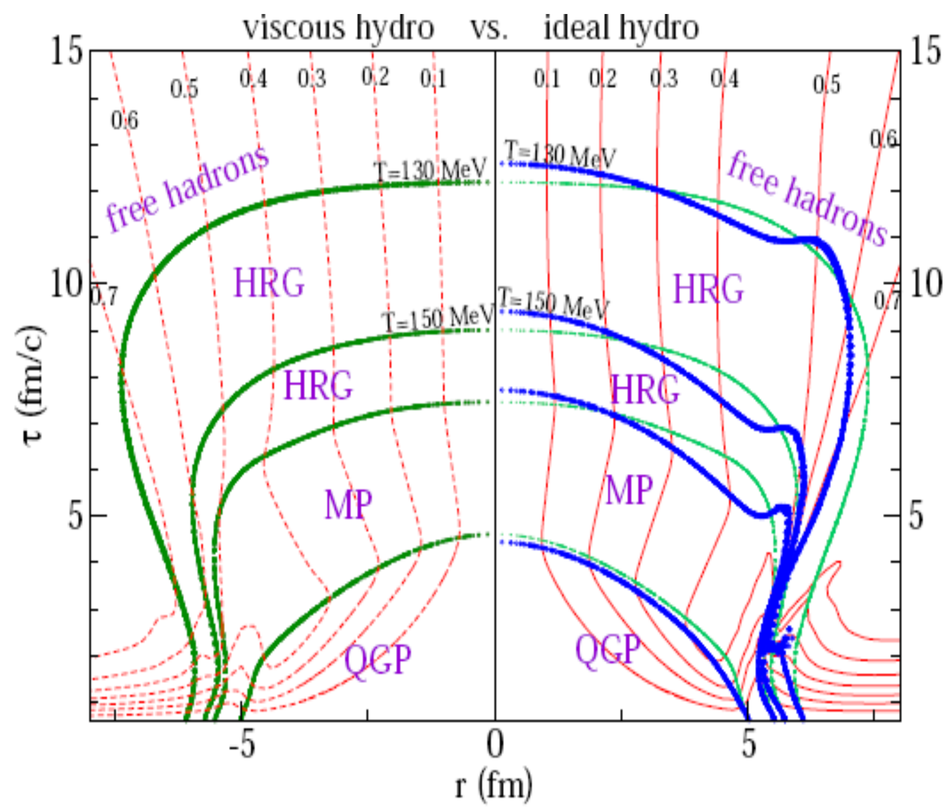
The world is much richer than just a HRG and a Stefan-Boltzmann QGP!

Near-Tc Matter: Hydrodynamics

Near Tc Matter (between HRG and QGP) occupies
large space time volume (~1/3) during the fireball evolution.

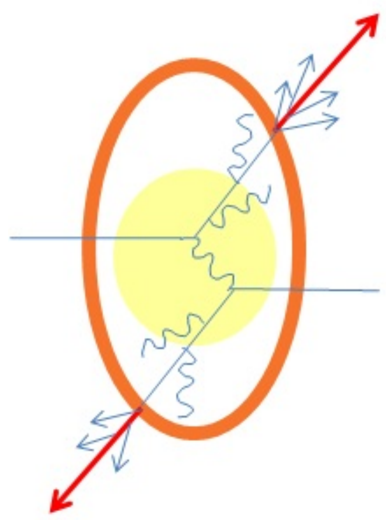


Teaney & Shuryak



Heinz & Song

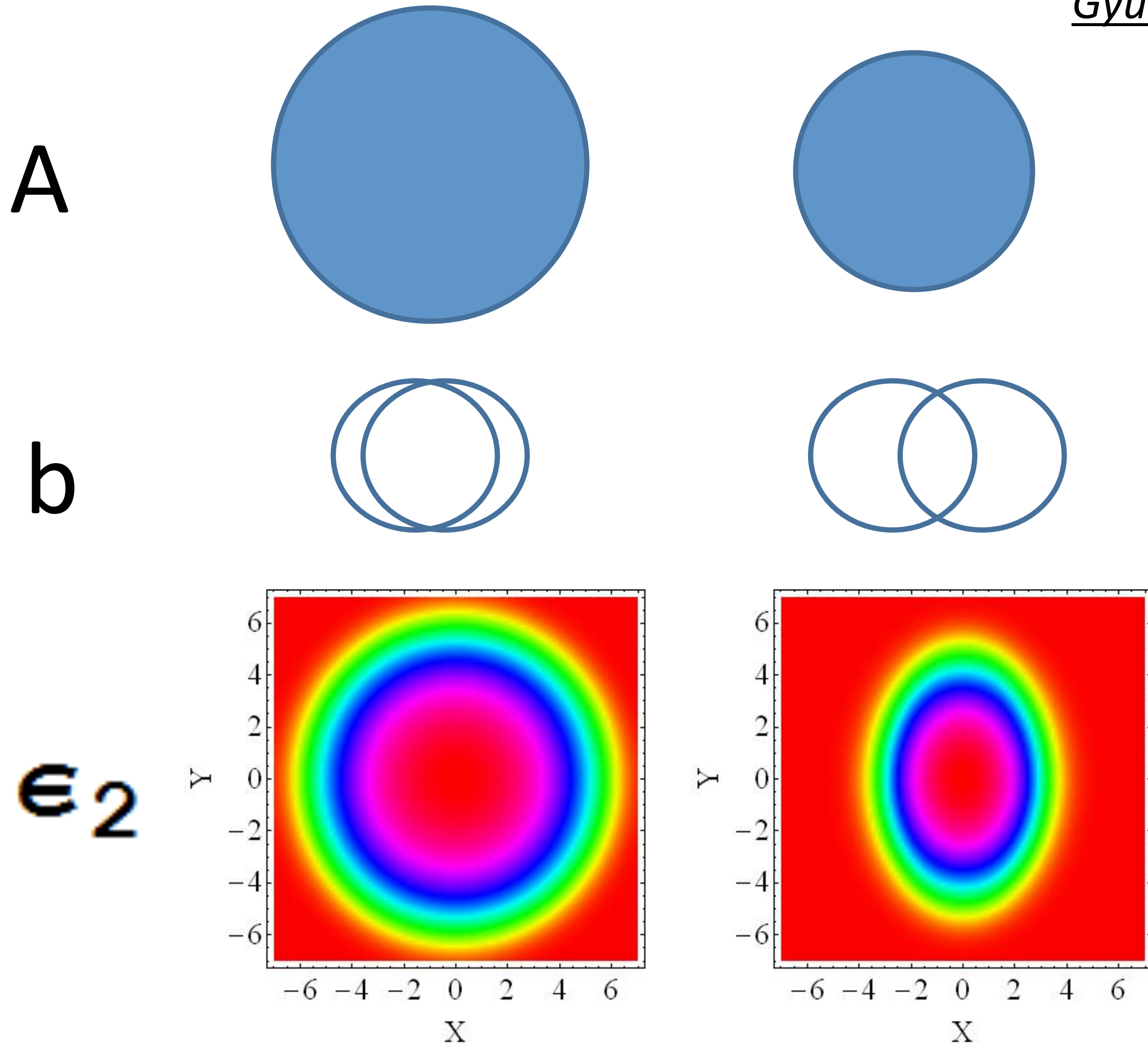
The Geometry and Physic ofJet Quenching



Geometric Tomography

Geometry of nuclei and geometry of collisions play essential roles in jet quenching.

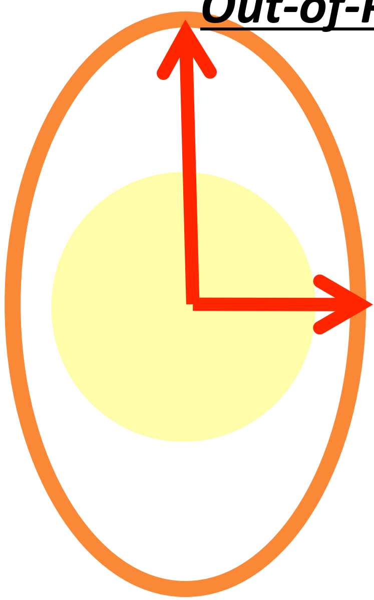
Gyulassy, Vitev, Wang; ……



Same dynamics, different geometry → predictable change in exp. outcome with geometry!

Geometric Data: V2(hard)

Non-central collision → matter spatial anisotropy → quenching anisotropy



$$R_{aa}\ (\phi)$$

$$I_{in} < I_{out} \Rightarrow (R_{aa})_{in} > (R_{aa})_{out}$$

Positive v2 for high Pt particles:

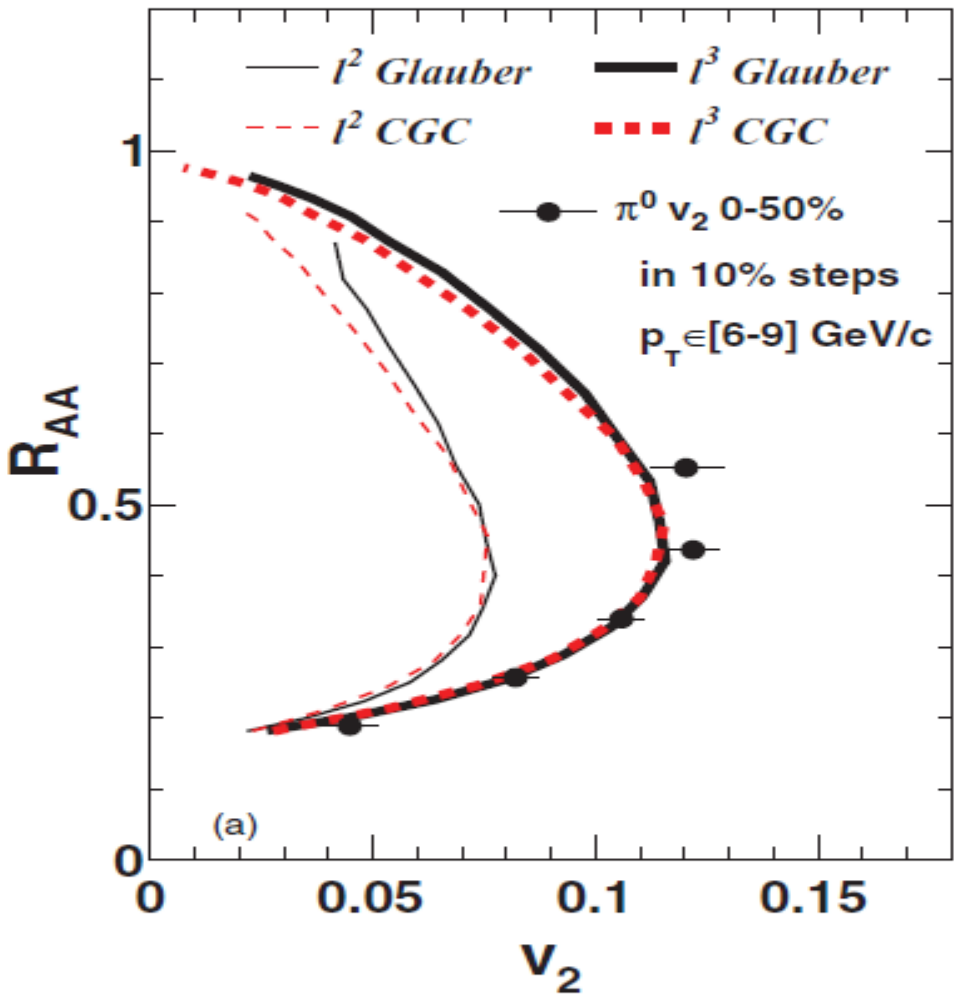
$$v_2\ (\mathrm{high}\ P_t) = \frac{(R_{aa})_{in} - (R_{aa})_{out}}{2[(R_{aa})_{in} + (R_{aa})_{out}]}$$

More sensitivity, better discriminating power

In the last 2-3 years: fluctuations bring even more interesting geometry!!

Correlated Geometric Observables

Jia, Horowitz, JL, Phys.Rev. C84 (2011) 034904



And many more multi-observable correlations to constraint models:

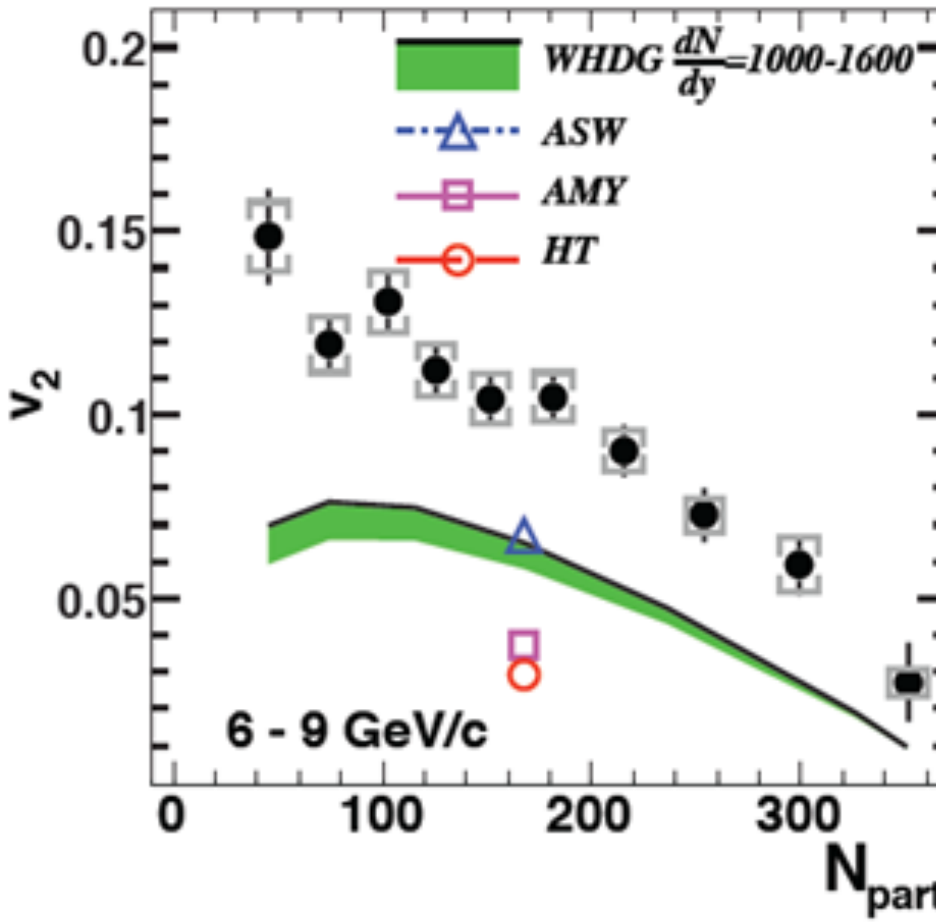
Raa, V2, Iaa, V2_Iaa, …

NOW EVEN MORING INTERESTING:
V1, V3, V4, V5, V6, …
Need to be studied !

(Please come to XILIN ZHANG's Nuclear Seminar Tomorrow On hard probe of geometry and fluctuations!)

A Bit of History

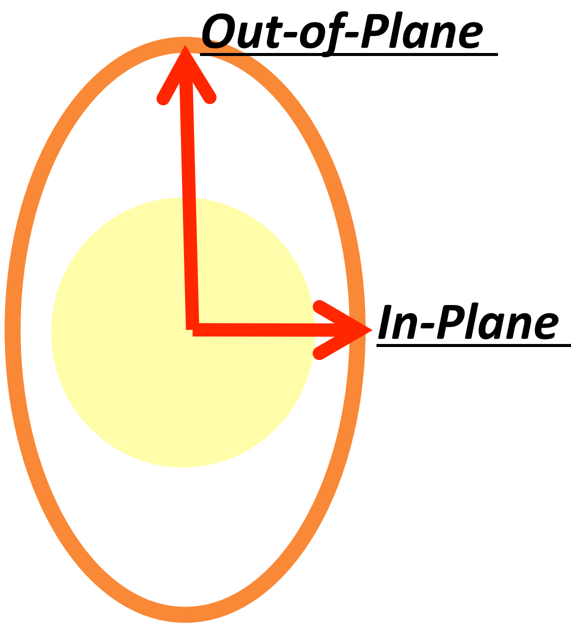
- Gyulassy-Vitev-Wang (01); Wang (01): pQCD based model predictions
- STAR preliminary data showed m
- Shuryak (01): completely opaque
  hard sphere geometry →
- More data out, till Pt~6GeV, the
- Drees-Feng-Jia (05): more realist
  various path dependence,
- pQCD based models continued t
- PHENIX Run4 data, Run7 prelimi
  → rather flat above 6GeV
- ??? "an area that is kind of stuck
  of ideas how to proceed"



Till about ~ 2008:

previous models failed to describe the (already high quality) geometric data: producing <u>too small anisotropy (V2)</u> with fixed opacity (Raa).

Pinning the Right Geometry

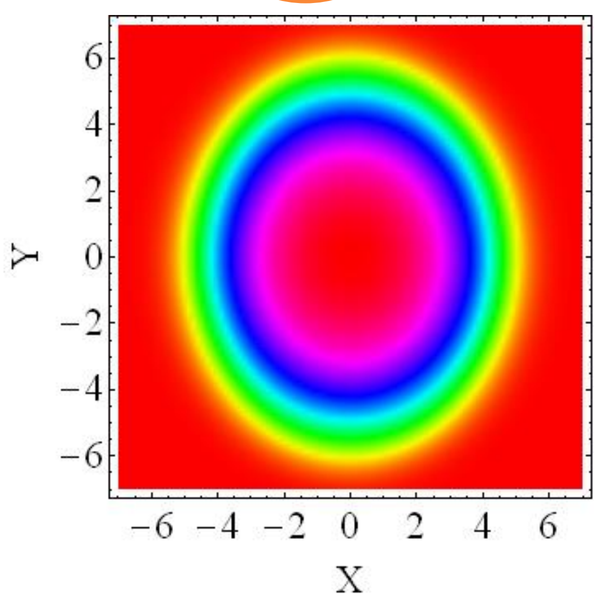


$$R_{aa}\ (\phi)$$

The puzzle may concern more radical questions:

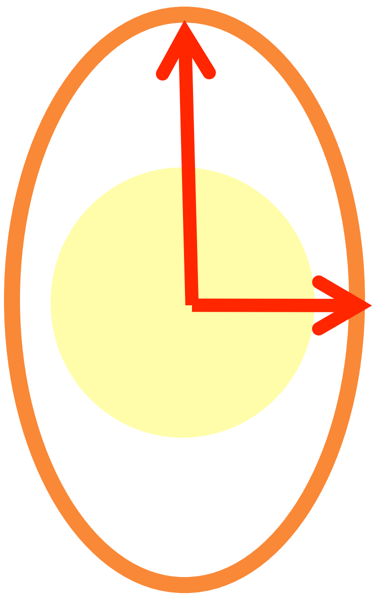
Where are jets quenched ???

JL & Shuryak, PRL102:202302,2009



"Egg yolk" has one geometry,
"Egg white" has another:
overall opacity can not tell →
measure geometry to pin physics

The "Egg Yolk v.s. White"

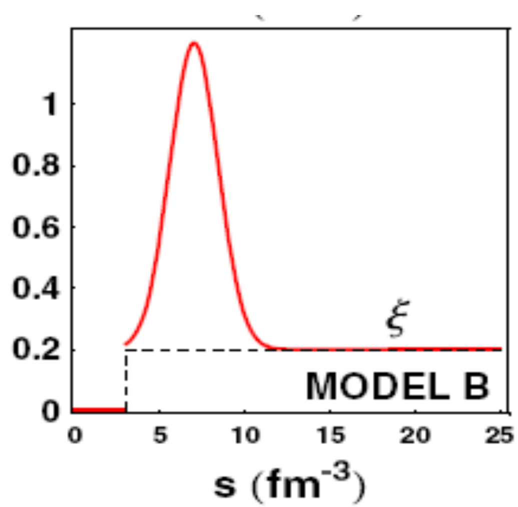


$$\boxed{I = \int_{path} \kappa[s]\, s\;\; x^n\, dx}$$

<u>Taken for granted in ALL previous models:</u>

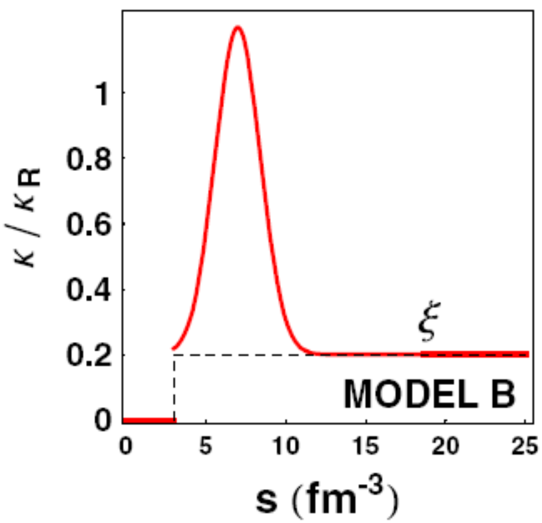
$$\kappa[s] \Rightarrow \text{constant}$$

Instead, we think it shall <u>have non-monotonic dependence,</u> particularly enhanced near the phase boundary due to Nonperturbative dynamics related to confinement!

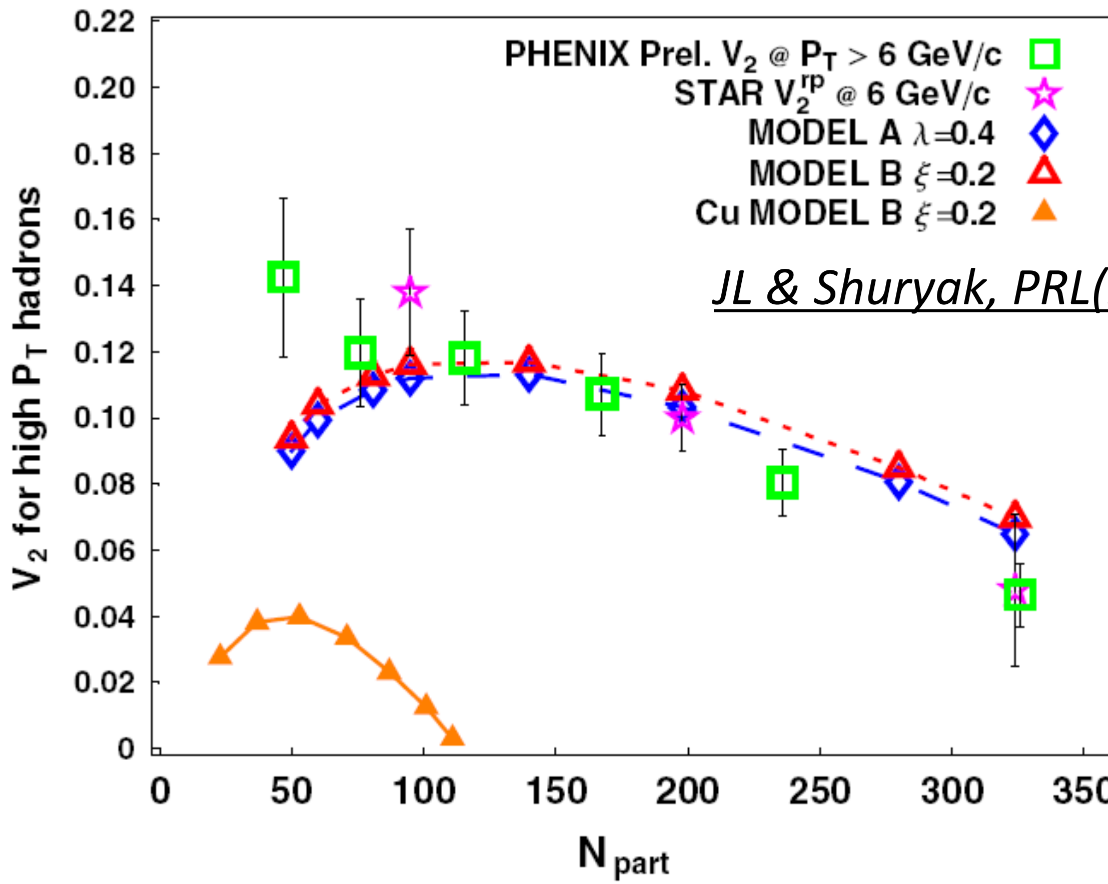


With such strong enhancement
→Enhance quenching at late time
→ Pick up more the "egg white" geometry

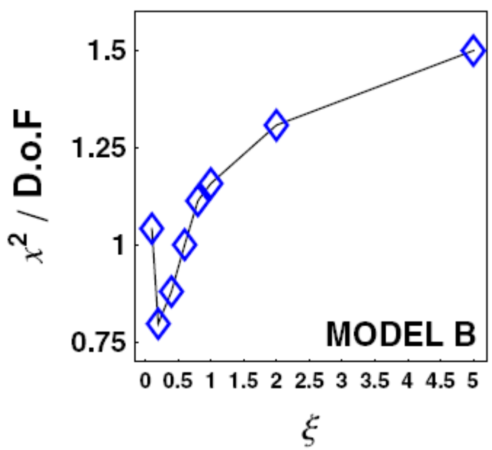
Near-Tc Enhancment Explains Geometric Data



Two components: near Tc & QGP.



JL & Shuryak, PRL(2009)



Data favors \xi~0.2: VERY strong enhancement of jet quenching in near Tc matter !

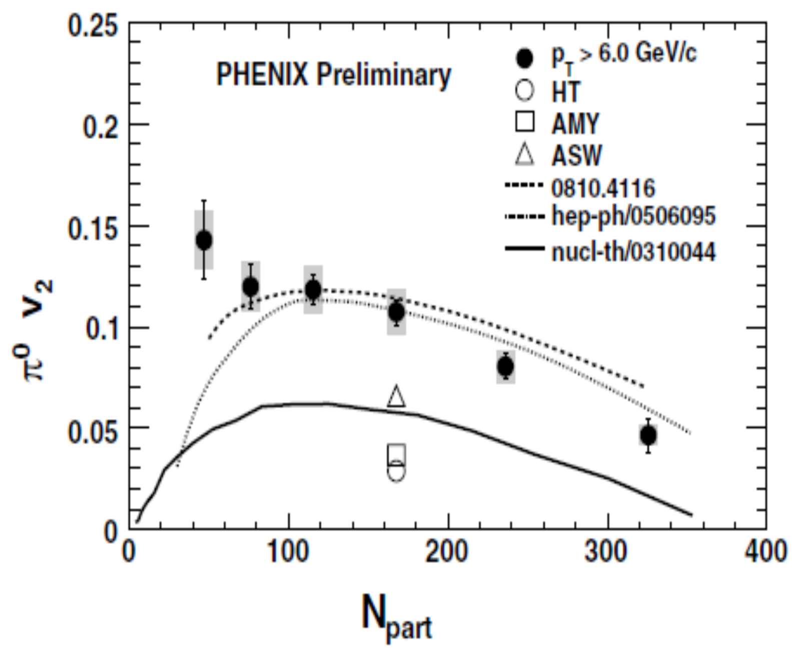
Near-Tc Enhancment Explains Geometric Data

PHYSICAL REVIEW C **80**, 054907 (2009)

High-p_T π^0 production with respect to the reaction plane in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

S. Afanasiev,[17] C. Aidala,[7] N. N. Ajitanand,[43] Y. Akiba,[37,38] J. Alexander,[43] A. Al-Jamel,[33] K. Aoki,[23,37] L. Aphecetche,[45] R. Armendariz,[33] S. H. Aronson,[3] R. Averbeck,[44] T. C. Awes,[34] B. Azmoun,[3] V. Babintsev,[14] A. Baldisseri,[8] K. N. Barish,[4] P. D. Barnes,[26] B. Bassalleck,[32] S. Bathe,[4] S. Batsouli,[7] V. Baublis,[36] F. Bauer,[4] A. Bazilevsky,[3] S. Belikov,[3,16,*] R. Bennett,[44] Y. Berdnikov,[40] M. T. Bjorndal,[7] J. G. Boissevain,[26] H. Borel,[8] K. Boyle,[44] M. L. Brooks,[26] D. S. Brown,[33] D. Bucher,[29] H. Buesching,[3] V. Bumazhnov,[14] G. Bunce,[3,38] J. M. Burward-Hoy,[26] S. Butsyk,[44] S. Campbell,[44] J.-S. Chai,[18]

One potential resolution of the problem with energy-loss calculations not reproducing the measured azimuthal dependence of yields is a recent calculation that allowed the high-p_T parton to resonantly scatter with the medium [33], increasing the energy lost by a parton at plasma densities that correspond to temperatures near the critical temperature. This produces a sharper dependence of the energy loss on the spatial variation of the medium's energy density and hence the model is able to simultaneously reproduce both $R_{AA}(p_T)$ and $R_{AA}(\Delta\phi)$. A critical check will be to examine whether the same parameters work for the full range of collision centralities.



Later Developments

- confirmation of near Tc scenario in e.g. GLV,ASW type of jet quenching models

  Renk-Holopainen-Heinz-Shen (arXiv:1010.1635)

  Francesco-Di Toro-Greco (arXiv:1009.1261)

  Fries & students (to appear)

- some near-Tc mechanism (pre-hadron loss in resonance matter; radiation of Cherenkov meson)

  Pirner, et al (arXiv:1010.0134)

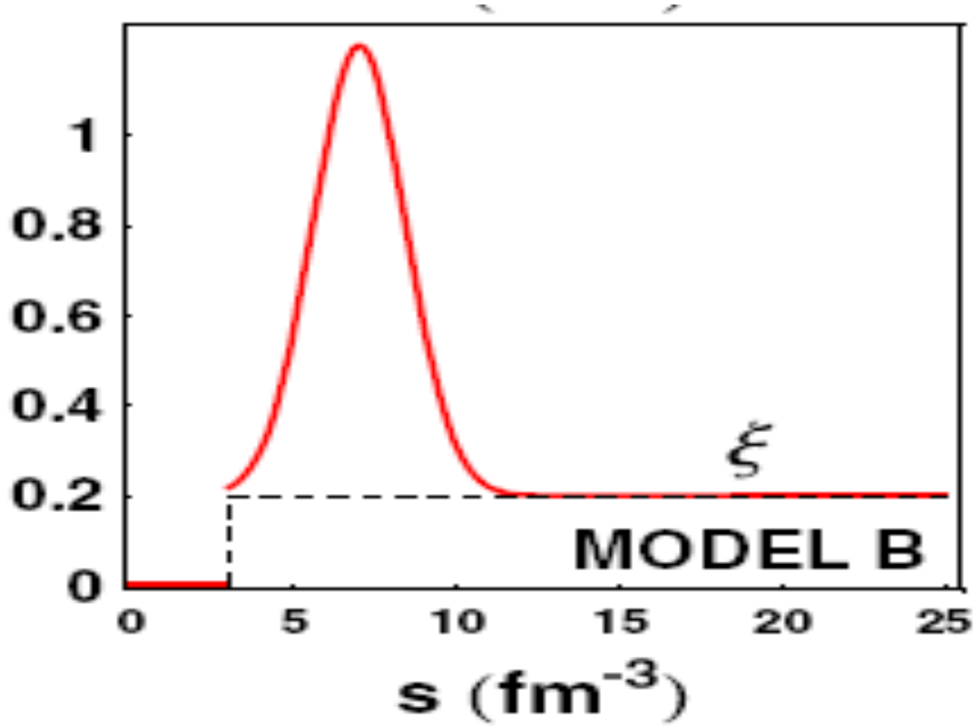
  [Panuev, formation time ~3fm]

  Casalderrey-Solana, et al (arXiv:1009.5937)

- *alternative late-stage jet quenching via L^3 path-length dependence (holography)*

  Marquet & Renk; Jia & Wei; et al.

From RHIC to LHC (NEW)



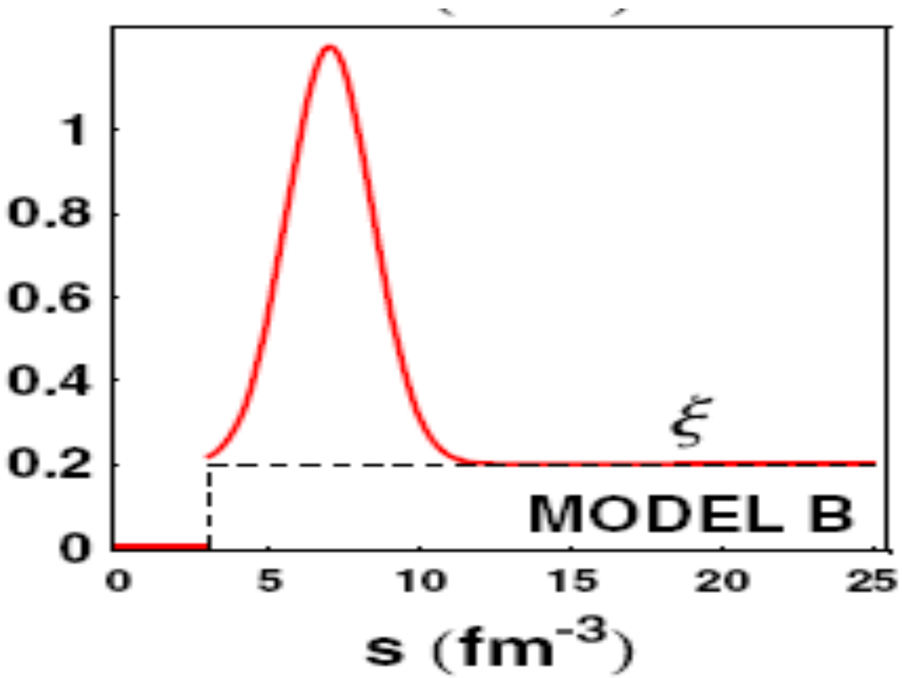
◆ over-quenching if one simply uses the same average "opaqueness" from RHIC

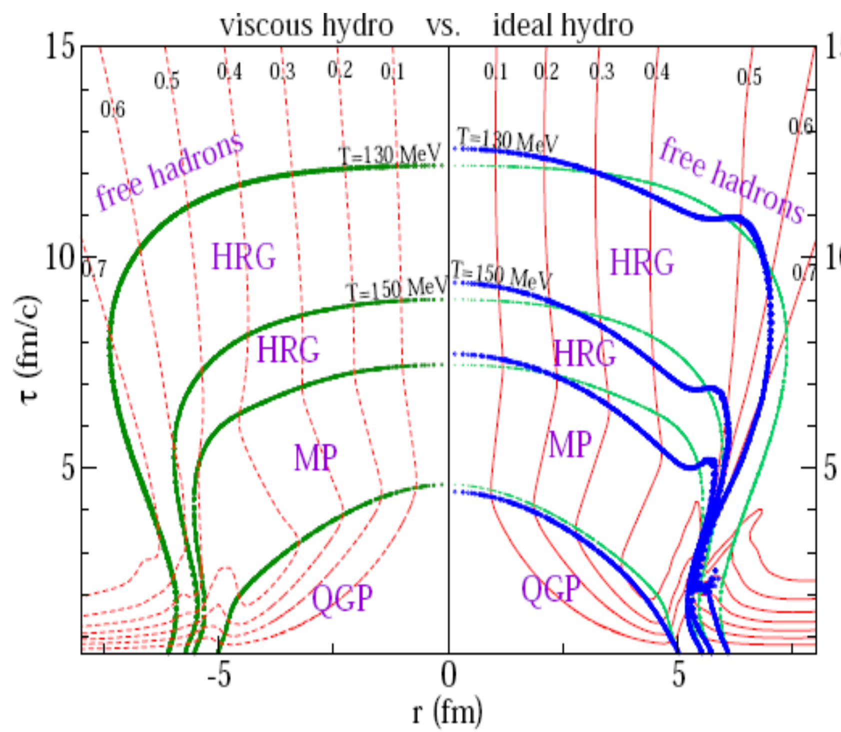
◆ at LHC, weighing more in much higher density

--- expect decrease of average jet-medium coupling

---- to be short, q-hat is NOT simply scaling up with ensity/ mulitiplicity

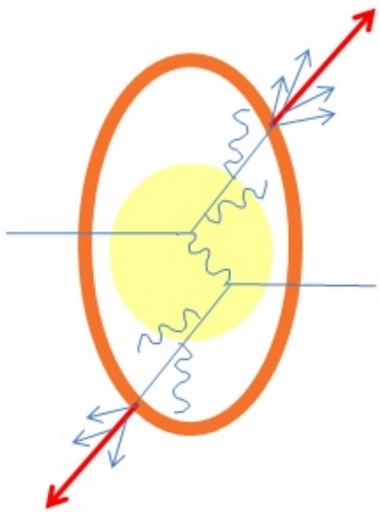
From RHIC to LHC: Shifting to Higher Density





The fireball evolution weighs much more in the higher QGP phase and gets less sensitive to the near Tc region when going to the LHC.

In the New Era of RHIC+LHC



$$f_P = exp\left\{-\int_P \kappa[s(l)]\, s(l)\, l^m dl\right\}$$

$$R_{AA}(\phi) = <\ (f_P)^{n-2}\ >_{P(\phi)}$$

Using ***the geometry of jet quenching*** at RHIC+LHC

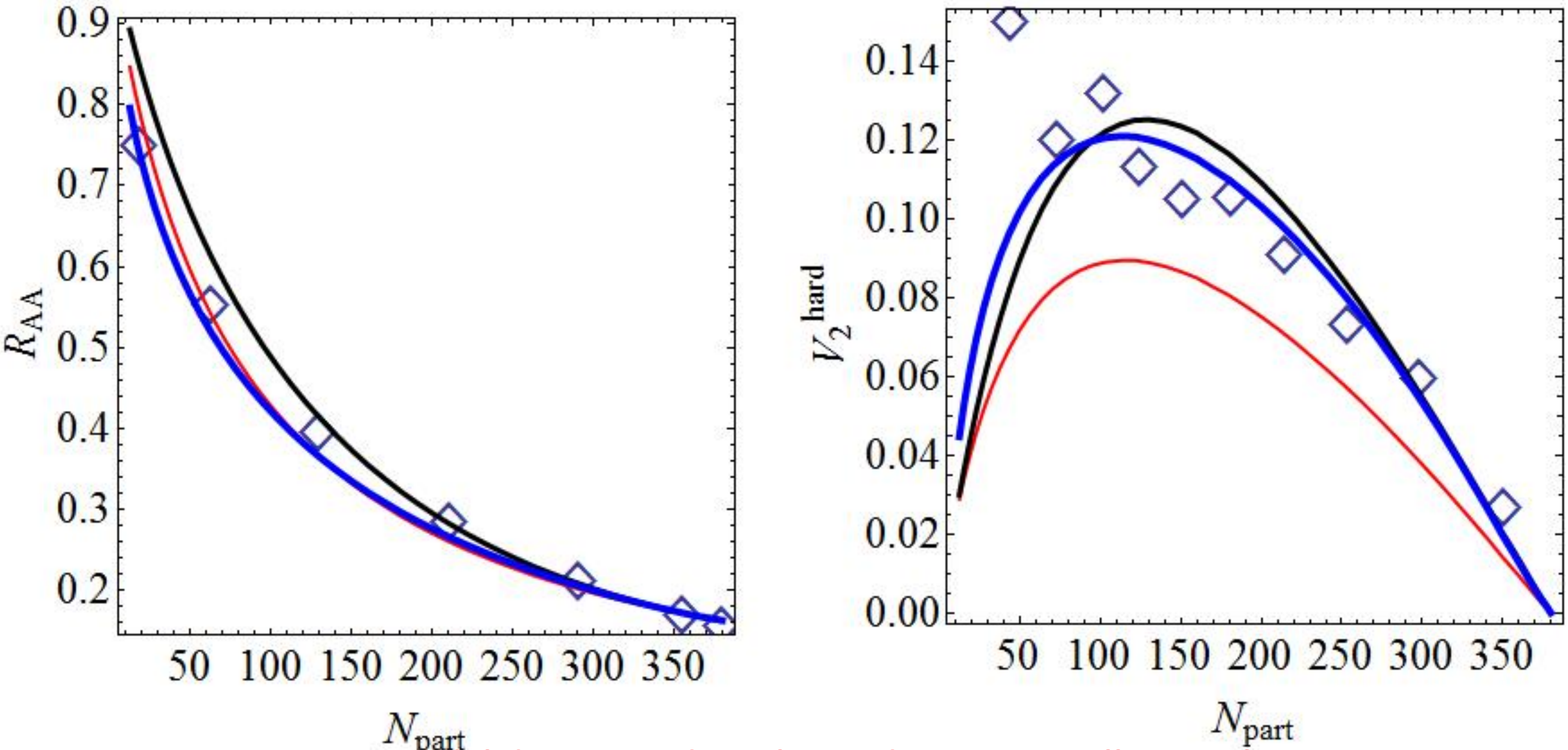
to answer questions about ***the physics of jet quenching***:

- **Is the near-Tc enhancement consistent, and necessary with both the RHIC and LHC data?**
- **Is the path-length dependence L^2 or L^3?**

JL, arXiv:1109.0271 [nucl-th]

Geometric Data & Modeling @ RHIC

RED: L^2 model **BLUE: L^2 + Near-Tc** **BLACK: L^3 model**



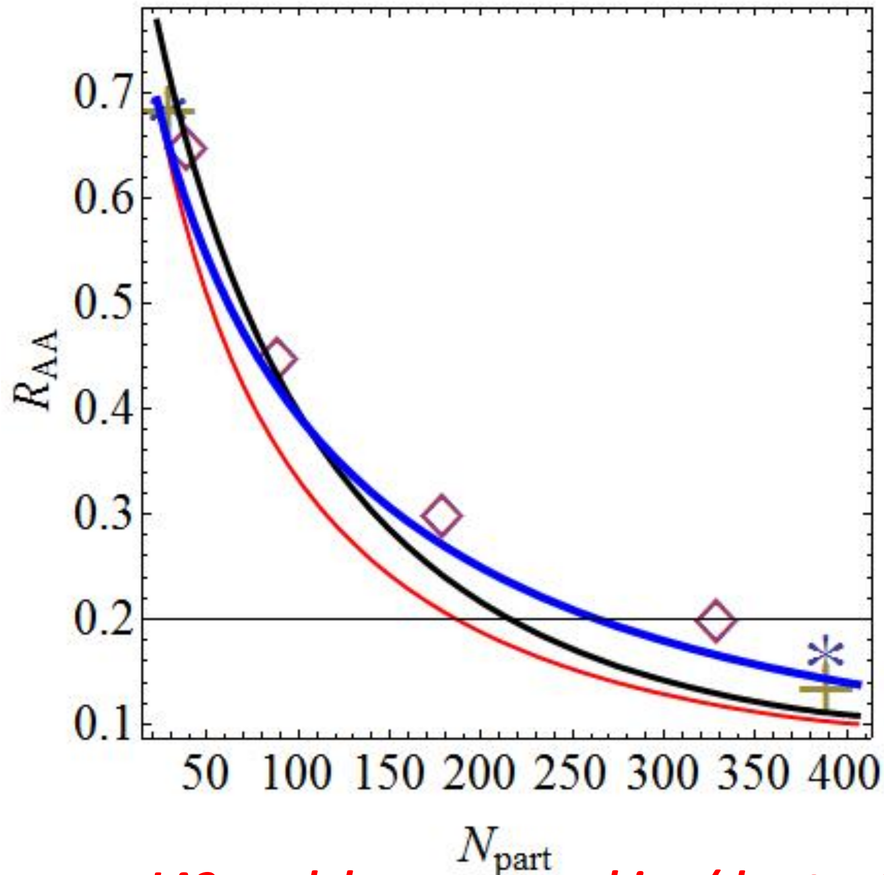
L^2 model does NOT describe v2 data across all centrality.

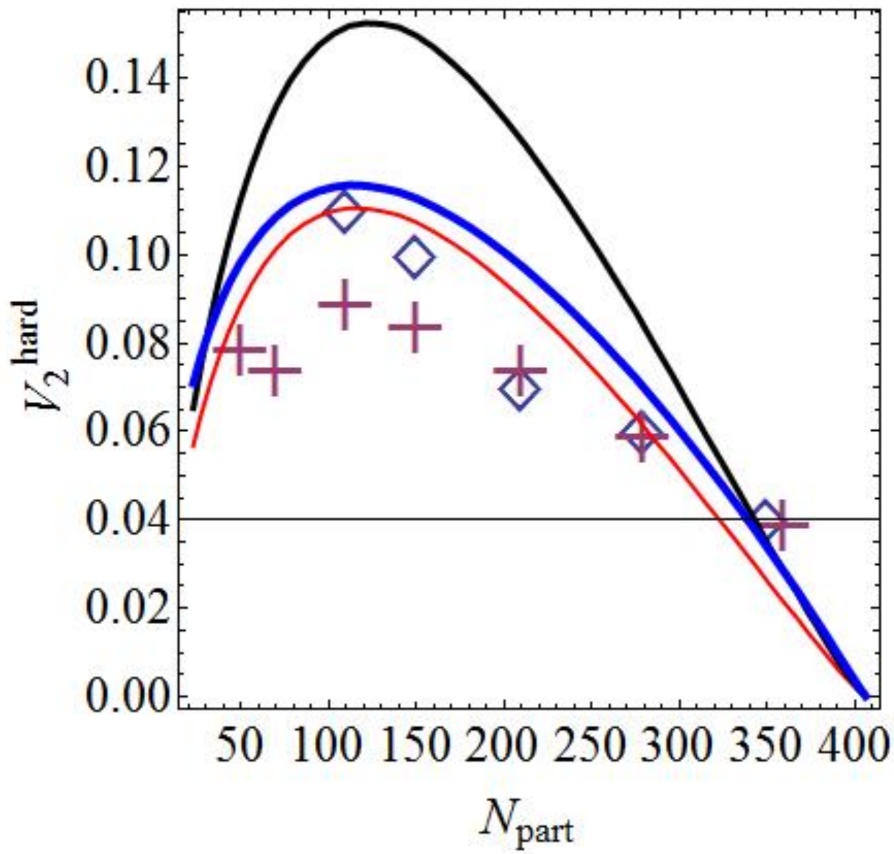
L^2 with near-Tc enhancement AND L^3 model both are OK
--- they both effective enhance later-stage quenching!

JL, arXiv:1109.0271 [nucl-th]

Geometric Data & Modeling @ LHC

RED: L^2 model   **BLUE: L^2 + Near Tc**   **BLACK: L^3**





***L^2 model :** over quenching (due to strong density scaling-up); describing v2 OK.*

***L^2 model :** too much anisotropy (due to strong path-length power); describing Raa OK.*

***L^2 with near-Tc enhancement:** describe both Raa and V2 very well !*

JL, arXiv:1109.0271 [nucl-th]

Tomo- v.s. Mono- v.s. Holo- Graphy

- Jet quenching: geometric data provides essential test for the dynamics of jet-medium interaction.

	Raa @RHIC	V2(hard) @RHIC	Raa @LHC	V2(hard) @LHC
L^2 model	√	×	×	√
L^2 + near-Tc	√	√	√	√
L^3 model	√	√	√	×

- Precision RHIC data & preliminary LHC data together are in favor of the model with

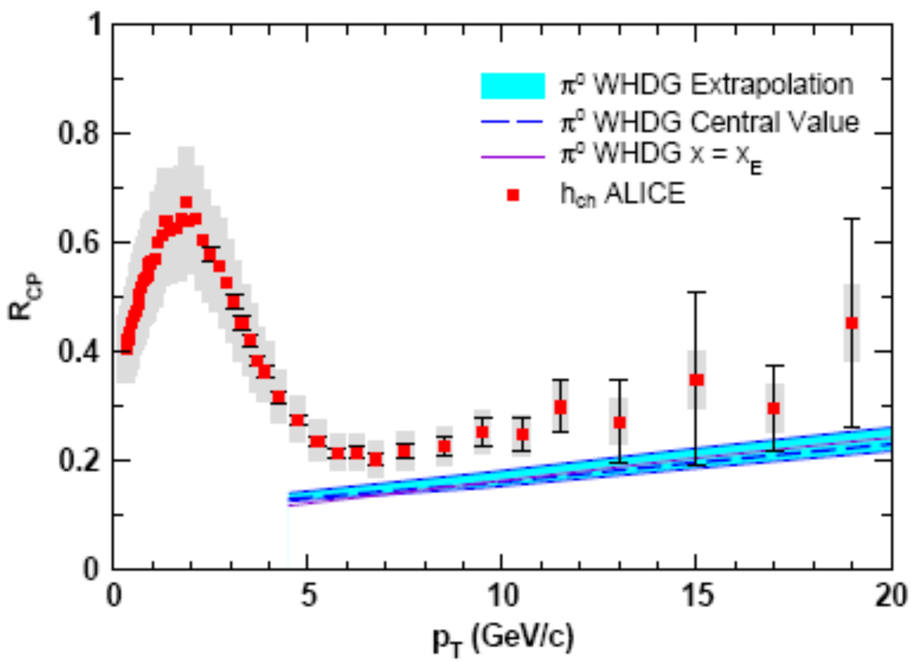
strongly enhanced jet quenching in near-Tc matter!

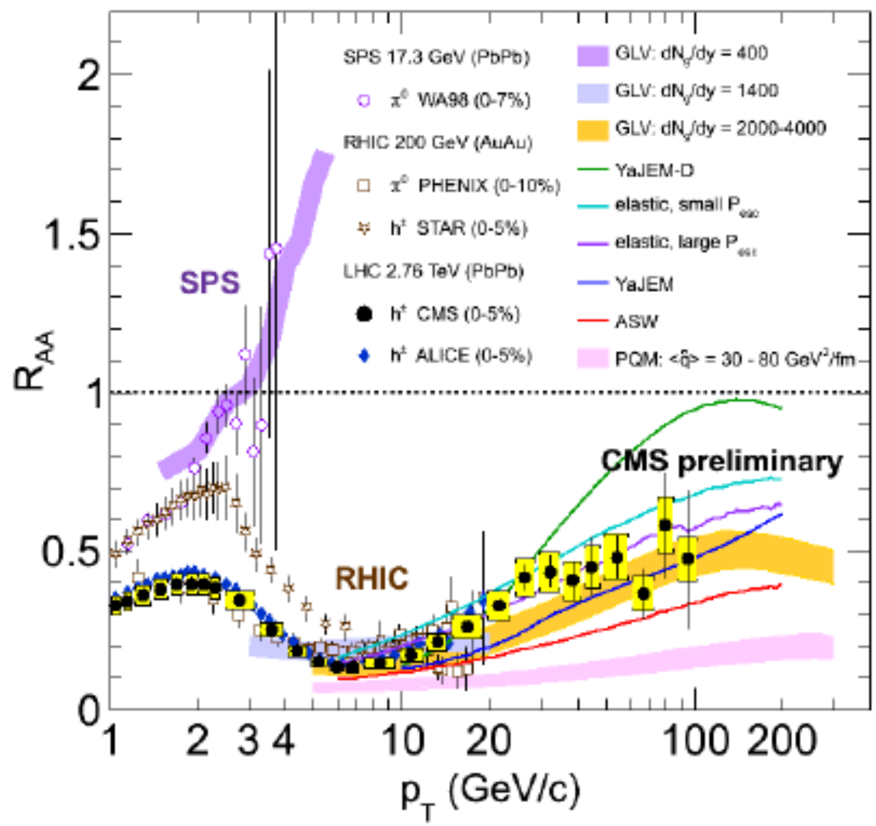
JL, arXiv:1109.0271 [nucl-th]

Medium More Transparent @ LHC?!

Horowitz & Gyulassy, arXiv:1104.4958

GLV/WHDG: "surprising transparency of sQGP at LHC"?!
(using the same coupling at RHIC and scaling up with density)



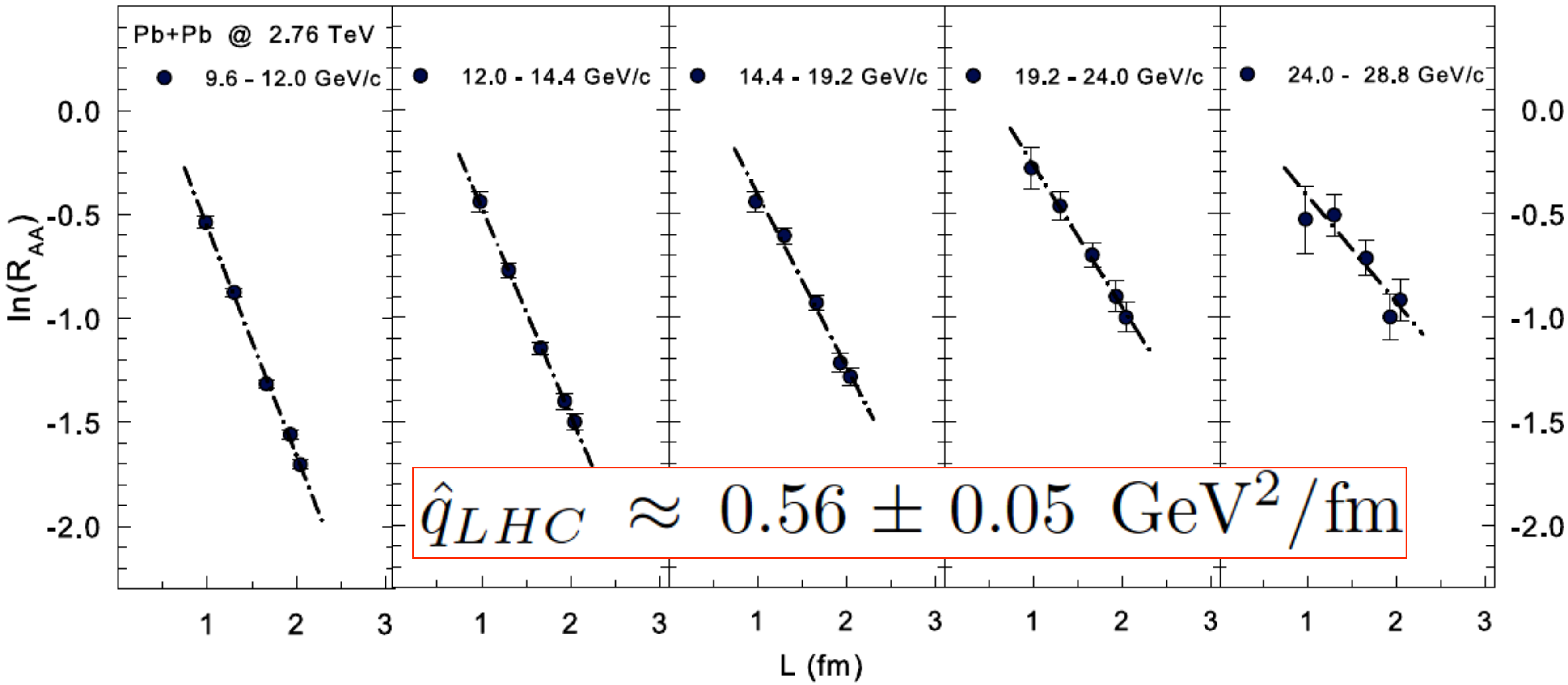


ALICE & CMS results at QM11

Medium more Transparent @ LHC?!

Lacey, Jia, et al, arXiv:1203.3605; 1202.5537

Applying the same scaling analysis for DATA at RHIC & LHC

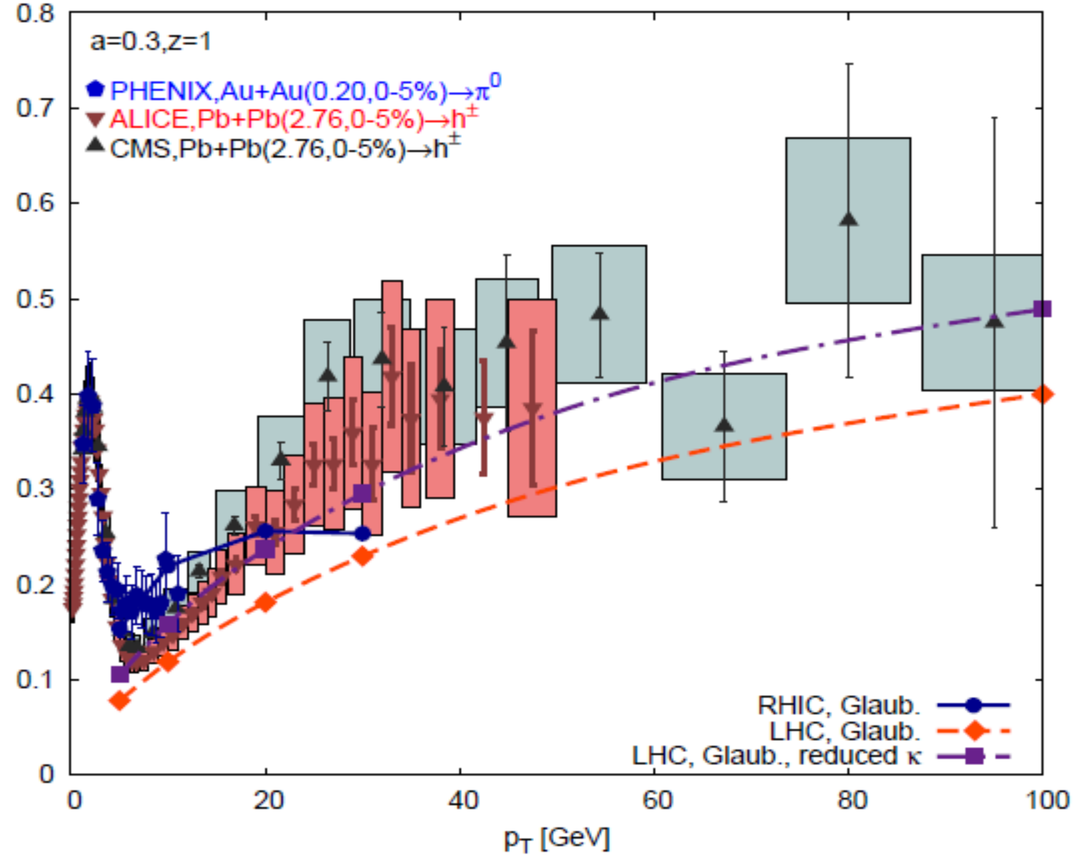


$$\hat{q}_{RHIC} \approx 0.75 \pm 0.05\ \mathrm{GeV}^2/\mathrm{fm}$$

These values are fireball-average and they FAIL to scale with density/multiplicity!!

Reduced Jet-Medium Coupling @ LHC

Betz & Gyulassy, arXiv:1201.0281



- over-quenching if one simply uses the same “opaqueness” from RHIC
- reducing jet-medium coupling by factor 2 for describing LHC data

$$\boxed{\kappa_{LHC} \approx (0.6 \pm 0.1)\kappa_{RHIC}}$$

Glimpse into Non-Purt. Running?!

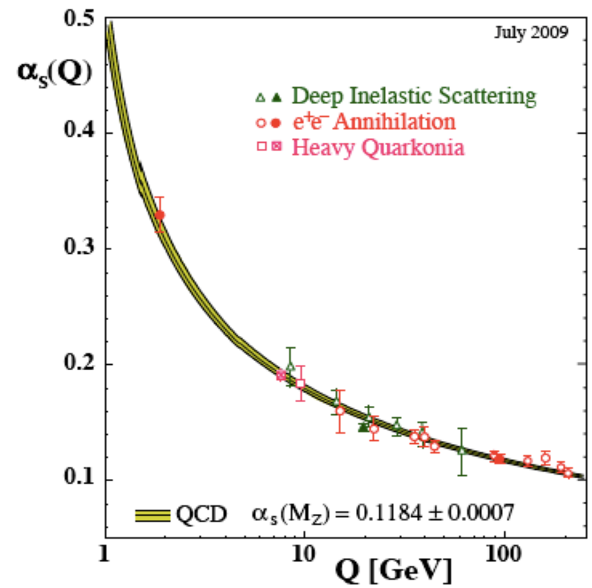
$\boxed{T\,(LHC) \simeq 1.3 * T\,(RHIC)}$

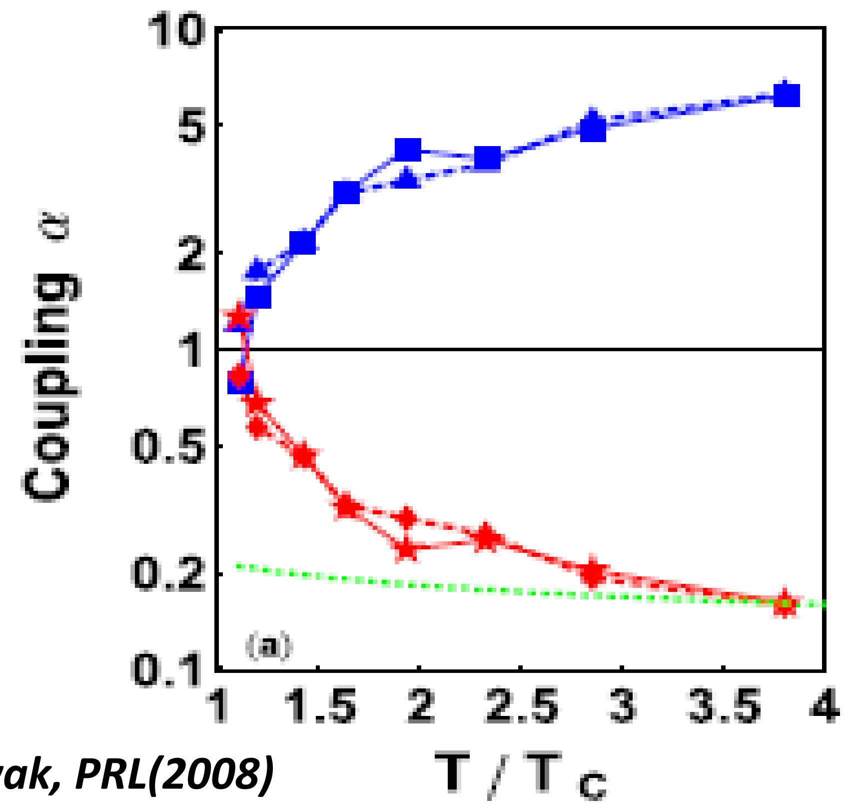
Betz & Gyulassy, arXiv:1201.0281:

$\boxed{\alpha\,(LHC) \simeq (80 \sim 90)\,\% * \alpha\,(RHIC)}$

Zakharov, arXiv:1105.2028

$\boxed{\alpha\,(LHC) \simeq (70 \sim 80)\,\% * \alpha\,(RHIC)}$





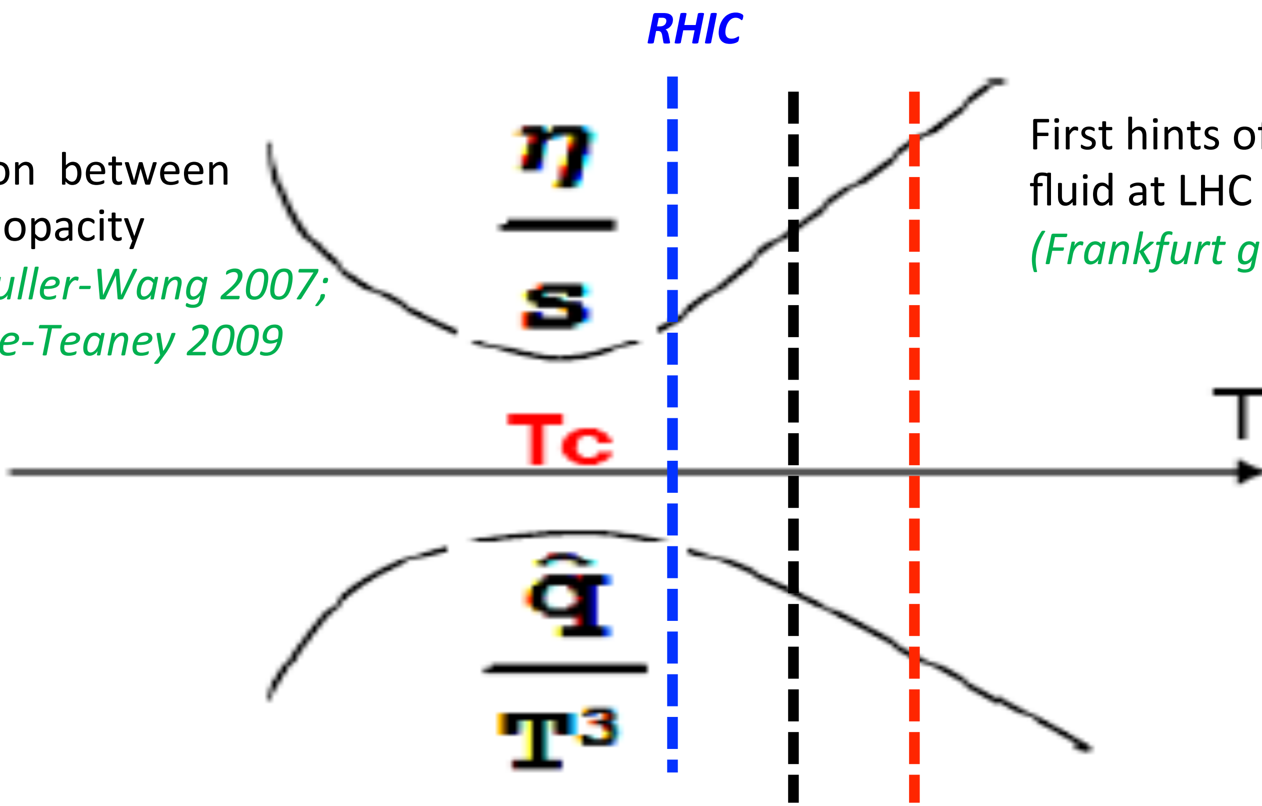
JL & Shuryak, PRL(2008)

This is very exciting !!

LHC @ 5.5TeV:
a "big" step toward AFM?!

Quenching & Viscosity Linked-up: from Near Tc to Higher T

Inverse relation between viscosity and opacity
Majumder-Muller-Wang 2007; Dusling-Moore-Teaney 2009



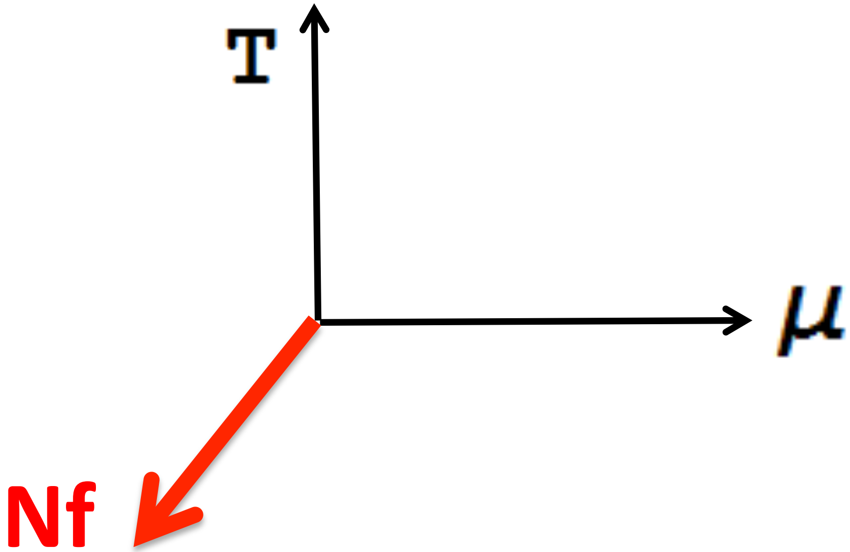
First hints of "less-perfect" fluid at LHC 2.76TeV?!
(Frankfurt group; Ohio group)

LHC: 2.76 → top energy, exciting possibility!

Will we see a systematic deviation from RHIC to LHC?

Rapid change in a narrow regime 1-3Tc.

Exploring One More Dimension of the Phase Diagram



Adding Light Fermions

- Varying the matter content in QCD-like theories: Number of flavors; representation of the fermions

- These provide very useful information on understanding the non-Abelian gauge theory dynamics

- For example, their effects on beta-functions:

$$\beta(g^2) = \frac{dg^2}{d\log\mu^2} = -\left[\frac{b_0}{(4\pi)^2}g^4 + \frac{b_1}{(4\pi)^4}g^6 + \ldots\right]$$

$$b_0 = \frac{11}{3}C_2(G) - \boxed{\frac{4}{3}N_f T(r)}$$

$$b_1 = \frac{34}{3}[C_2(G)]^2 - \boxed{\frac{4}{3}N_f T(r)}[5C_2(G) + \boxed{3C_2(r)}]$$

How about the Transition?

- Effects of light fermions on confinement transition:

very useful information for understanding its mechanism
--- recall the importance of isotope effect in superconductivity

- How the confinement transition changes with fermion flavor number and representation?

--- Lattice gauge theory already tells us a lot about it.
e.g. Nc=3 pure glue → 1 flavor fun. → 2 → 3
The critical temperature drops a lot: 270MeV → 165MeV
Or equivalent to say the transition shifts to stronger coupling
(Caveat: fixing scale with vacuum string tension)

- Similarly increasing from fun. to adj. to sex. the transition shifts into stronger coupling regime

All very interesting lattice findings , question is: why so?
Can we understand these from the near Tc plasma side?

Monopoles just about to Condense

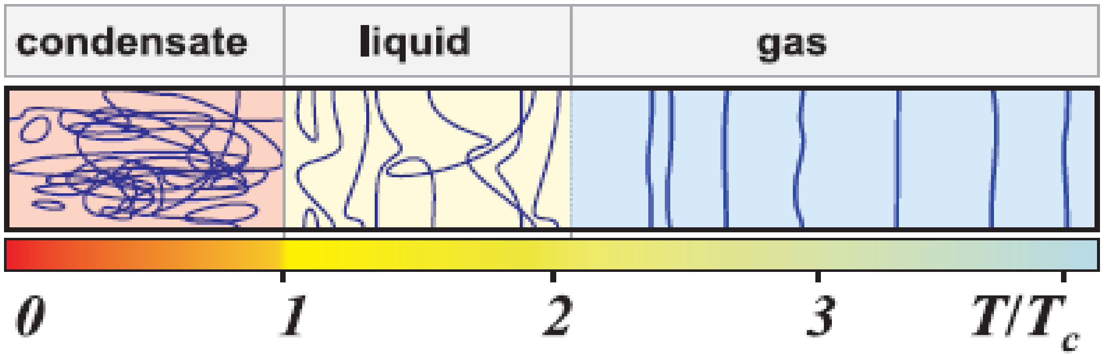
Near Tc plasma of monopoles:

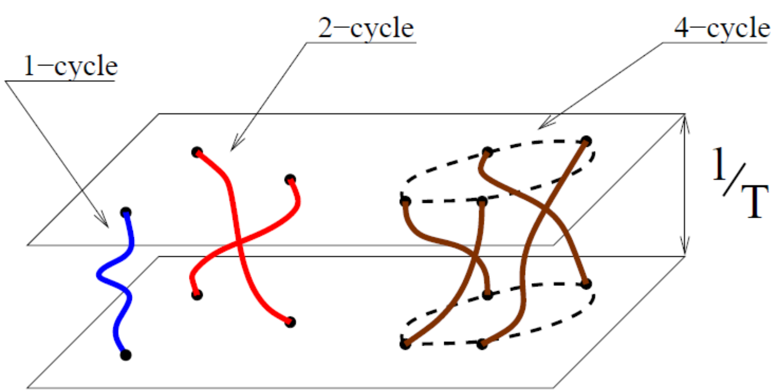
$$m^*/T \sim 1/g$$

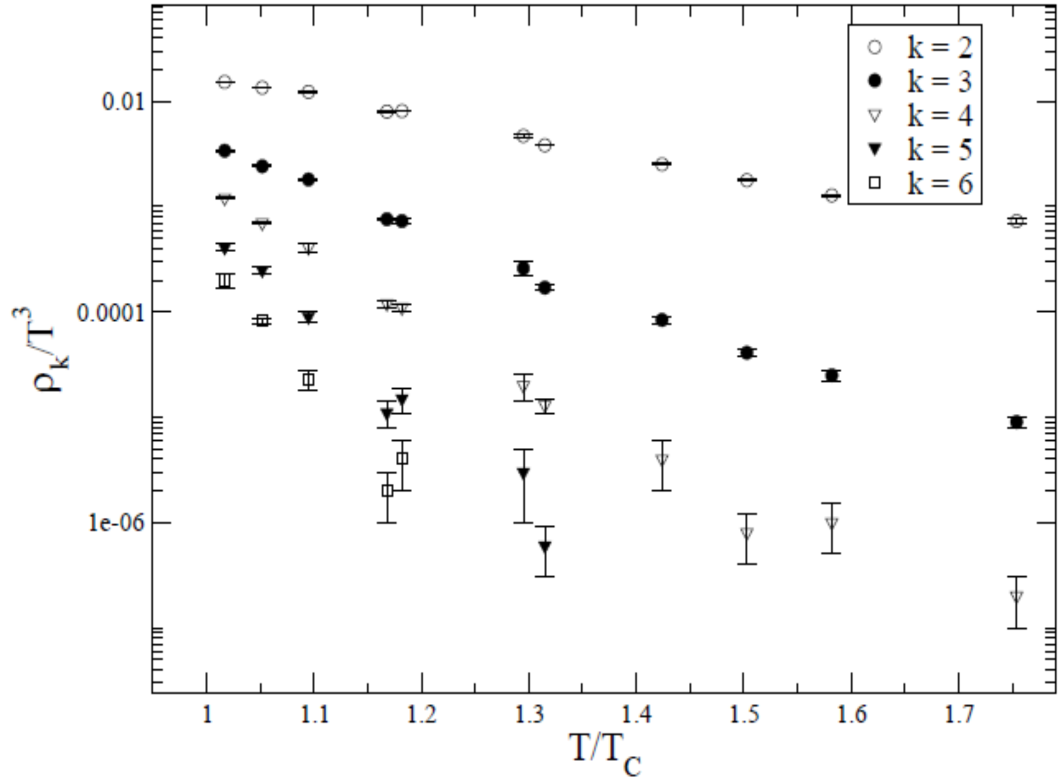
$$n^{1/3}/T \sim g^2$$

Feynman criteria for BEC:

$$\left(\frac{m^*}{T}\right)\frac{(1+f)^{4N_f N_M/3}}{(n/T^3)^{2/3}} \le \tilde{S}_c$$

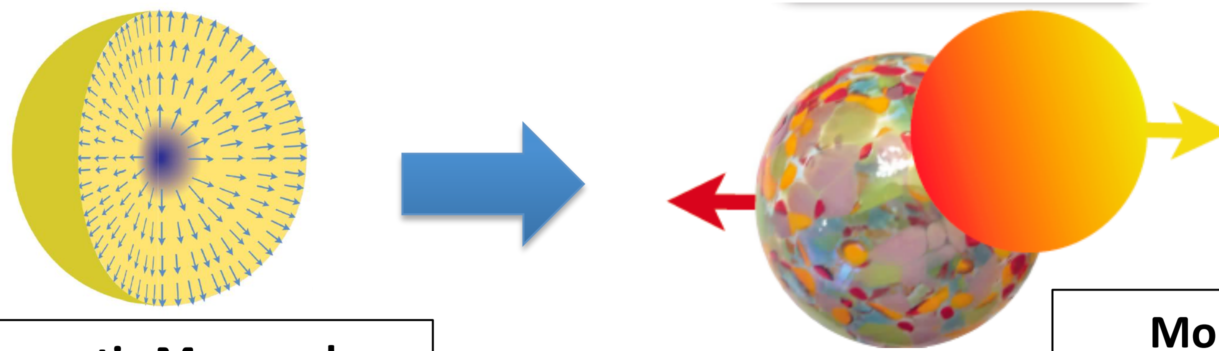






arXiv:1002.4161

Effect of Adding Fermions

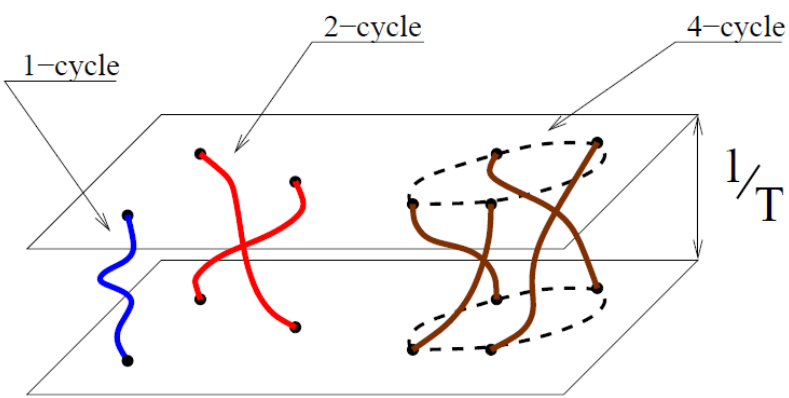


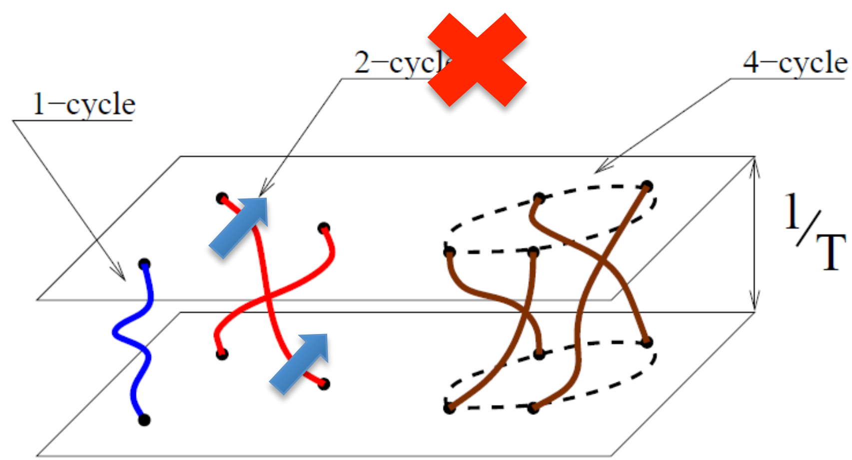
Magnetic Monopoles

Monopole-quark from zero modes

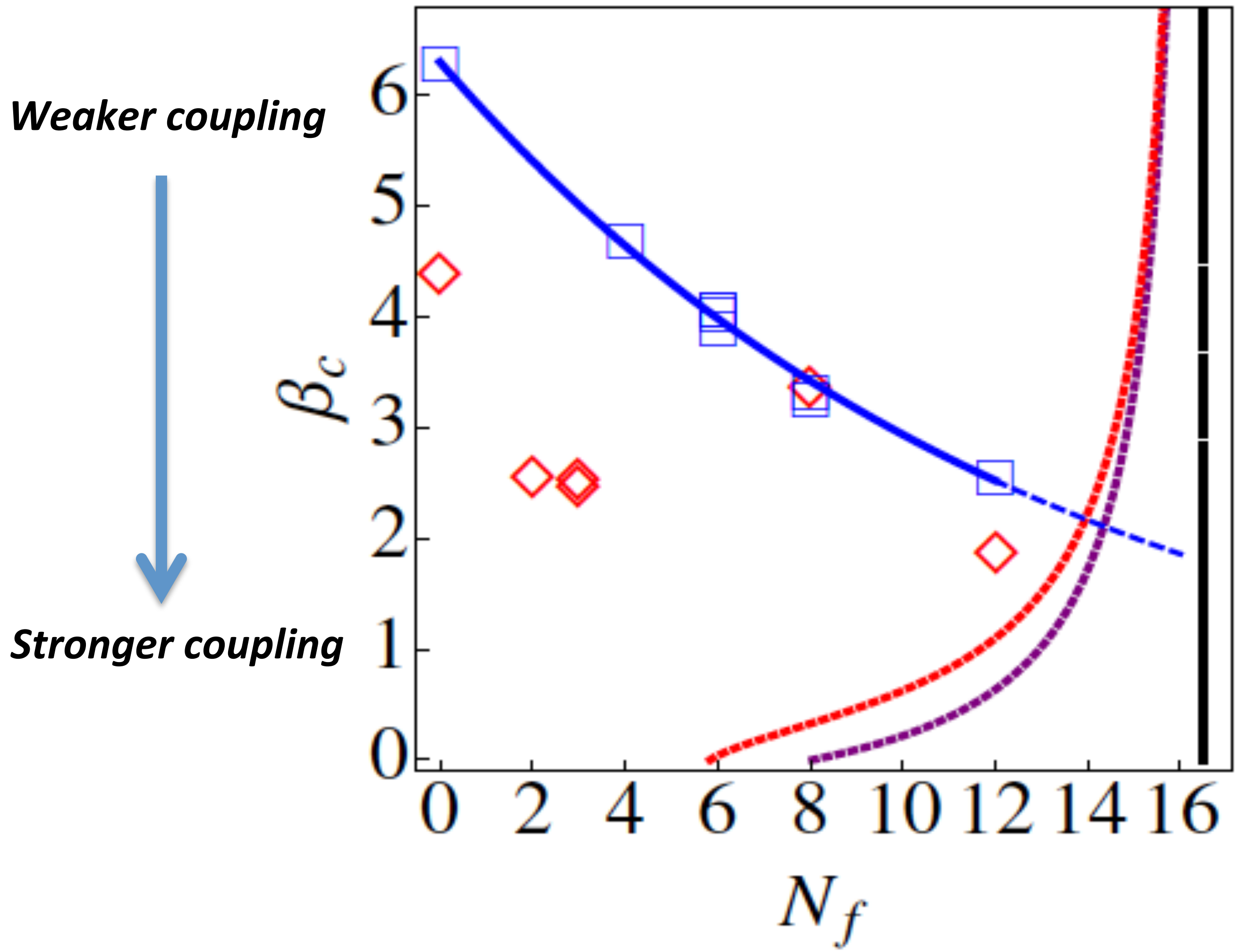
Monopole-quark states from zero modes attached to monopoles →

- dilution of pure monopoles, i.e. decreasing density at given coupling
- pushing condensation point to stronger coupling
- the more number of zero modes Nf*Nm , the stronger effect





The Critical Coupling v.s. Nf



$$\beta_c(N_f) = \beta_0(1+f)^{-8N_f N_M/15} \qquad f \approx 0.154$$

Additional Tests on Lattice

- **Dependence of transition on the B-chemical potential:**

$$\frac{\beta_c(N_f, z)}{\beta_c(N_f, z=0)} = 1 - \frac{4N_f N_M}{15} \frac{f}{(1+f)^2} z^2 + \hat{O}(z^4)$$

$$z \equiv \mu_q / T$$

- **Contribution of monopole-quark states to conserved charge fluctuations, i.e. various susceptibilities**

$$\chi_2^{m-q} \approx \frac{n}{T^3} \frac{2f}{(1+f)^{N_f N_M}} \sim 0.4 - 0.8$$

- **Direct "detection" of these states in the transition in dense phase of Nc=2 (without "sign problem")?**
  --- Hands et al, saw a rise in "quark"-density beyond the Fermi surface simultaneously upon deconfinement (via Polyakov line) at finite density low temperature.

Summary

- **Geometric tomography** provides essential information on the mechanism of jet quenching.
- **RHIC+LHC** supports a new picture on the question of

  "where are jets quenched (more strongly)?":

  strong jet quenching component at late stage,

  corresponding to the matter near phase boundary.

[Come to Nuclear Seminar tomorrow by Xilin Zhang on:

Hard probe of the fluctuating geometry from RHIC to LHC and

the hard-soft correlations (the hard ridge and the double-hump) and

geometry and fluctuations via jet quenching for LHC at 5.5TeV**]**

- **Lattice sees significant shift toward stronger coupling for confinement at large Nf: well described in the monopole condensation scenario by mechanism of fermionic zero modes**

  ---- many further tests suggested for lattice study